ELSEVIER

Agriculture, Ecosystems and Environment 88 (2002) 183–193

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop

R.A. Eigenberg [a,*], J.W. Doran [b], J.A. Nienaber [a], R.B. Ferguson [c], B.L. Woodbury [a]

[a] *Biological Engineering Research Unit, USDA-ARS US Meat Animal Research Center, P.O. Box 166, Clay Center, NE 68933, USA*
[b] *USDA-ARS Soil and Water Conservation Research, University of Nebraska, Lincoln, NE 68583, USA*
[c] *South Central Research and Extension Center, P.O. Box 66, University of Nebraska, Clay Center, NE 68933, USA*

Abstract

Development of sustainable agricultural management systems will depend, in part, on the ability to better use renewable resources, such as animal manure, and to synchronize the levels of soil available N with crop plant needs during the growing season. This study was conducted at the US Meat Animal Research Center in the central USA to determine whether differences in electromagnetic (EM) soil conductivity and available N levels over a growing season can be linked to feedlot manure/compost application and use of a green winter cover crop. A series of soil conductivity maps of a research cornfield were generated using global positioning system (GPS) and EM induction methods. The study site was treated over a 7-year period with manure and compost at rates matching either the phosphorus or the nitrogen requirements of silage corn (*Zea mays* L.). The plot was split for sub-treatments of a rye (*Secale cereale* L.) winter cover crop and no cover crop. Image processing techniques were used to establish electrical conductivity (EC) treatment means for each of the growing season surveys. Sequential measurement of profile weighted soil electrical conductivity (EC_a) was effective in identifying the dynamic changes in available soil N, as affected by animal manure and N fertilizer treatments, during the corn-growing season. This method also clearly identified the effectiveness of cover crops in minimizing levels of available soil N before and after the corn-growing season, when soluble N is most subject to loss. The EM method for assessing soil condition provides insights into the dynamics of available N transformations that are supported by soil chemical analyses. This real-time monitoring approach could also be useful to farmers in enhancing N use efficiencies of cropping management systems and in minimizing N losses to the environment.

Keywords: Electromagnetic induction; Soil electrical conductivity; Manure; Nutrient availability; Silage corn

1. Introduction

Evaluation of nutrient availability as a result of soil amendments such as livestock manure is difficult. Traditional methods of monitoring nutrients use soil cores to determine nutrient concentration at specific locations determined by conventional surveying methods. While this approach yields precision both in composition and position, it is expensive, time consuming, and may not account for spatial and temporal variability of measured attributes where animal manure is applied. Methods are needed to estimate the relative level of nutrients when manure is used. Geophysical methods have the potential to fulfill that need, with electrical conductivity (EC) as one geophysical tool that shows promise for agricultural applications.

Abbreviations: USMARC, US Meat Animal Research Center; EM, electromagnetic; GPS, global positioning system; EC, electrical conductivity; EC_a, profile weighted electrical conductivity

*Corresponding author. Tel.: +1-402-762-4272; fax: +1-402-762-4273.
E-mail address: eigenberg@mail.marc.usda.gov (R.A. Eigenberg).

0167-8809/02/$ – see front matter
PII: S0167-8809(01)00256-0

Instruments that measure soil conductivity without the use of soil probes are available commercially. These instruments use electromagnetic (EM) induction as a noninvasive method of measuring earth conductivity. Profile weighted soil electrical conductivity (EC_a) can provide an indirect measure of important soil properties (Sudduth et al., 2000). The EM instrument is sensitive to factors that influence soil conductivity, including: (1) soil moisture content; (2) amount and type of salts in solution; and (3) the amount and type of clays present (Brune and Doolittle, 1990). Electromagnetic techniques are well suited for mapping soil conductivity to depths useful for agriculturalists (McNeill, 1990). Electromagnetic terrain conductivity has been shown to be a very useful tool in locating seepage from animal waste lagoons (Ranjan et al., 1995). Sudduth and Kitchen (1993) used EM methods to estimate clay pan depth in soil. Electromagnetic methods have been used to map soil salinity hazards (Williams and Baker, 1982, Corwin and Rhoades, 1982). Electrical conductivity methods have been shown to be sensitive to high nutrient levels (Eigenberg et al., 1996, 2000) and have been used to detect ionic concentrations on or near the soil surface resulting from field application of cattle feedlot manure. Electrical conductivity has generally been associated with determining soil salinity; however, EC also can serve as a measure of soluble nutrients (Smith and Doran, 1996) for both cations and anions and is useful in monitoring the mineralization of organic matter in soil (De Neve et al., 2000). Doran et al. (1996) demonstrated the predictive capability of soil conductivity to estimate soil nitrate.

The objective of this work was to determine the utility of EC_a maps to determine the agronomic effectiveness and environmental consequences of N fertilization through varying application rates of compost, manure, and commercial fertilizer and use of cover crops. This 'time lapse' sequence was planned to allow observation of temporal field dynamics as a result of treatment application and biological activity. Image processing methods were used to extract treatment soil conductivity values of the field. Statistical tests were performed to determine if temporal effects of soil conductivity were significant for the manure, compost, and cover crop treatments. Correlations were computed for soil conductivity and measured soil constituents.

2. Methods

2.1. Site

A center-pivot irrigated field of silage corn (*Zea mays* L.) located at the US Meat Animal Research Center (USMARC) served as a comparison site for various manure and compost application rates for replacement of commercial fertilizer, with the same treatment assigned to field plots for 7 consecutive years. The soil series at this site is a Crete silt loam (fine, Montmorillonitic, Mesic Pachic Argiustolls), 0–1% slope. Five main plot treatments (6.1 m × 244 m) of manure and compost at rates matching either the phosphorus (P) or the nitrogen (N) requirements of the silage corn and a fertilizer N check at the recommended rate were replicated four times. The experimental field (244 m × 244 m) was arranged in a randomized complete block design with a split plot for winter cover crop (*Secale cereale* L.) versus no cover crop. Rates of application for the 1999 crop season are given in Table 1.

2.2. Field operations on the research cornfield

Field treatment nutrient application rates for each season were based on soil core analysis and plant chlorophyll measurements (Ferguson and Nienaber, 2000). Applications of two manure sources (beef feedlot manure and composted beef feedlot manure) were made each spring according to two strategies: (1) to approximately supply the total crop demand for N (252 kg N ha^{-1} average annual uptake), denoted MN and CN for manure and compost, respectively; or (2) to supply the approximate crop removal of P (45 kg P ha^{-1} annually), denoted MP and CP for manure and compost, respectively. Treatments MP and CP each had sufficient carry-over phosphorus in the 1999 season so that no manure or compost was applied to these treatment strips (6.1 m width of eight corn rows). Treatments MN and CN were the only treatments receiving manure/compost application on Julian Day (JD) 119–120 at total N rates of 249 and 222 kg N ha^{-1}, respectively (Table 1). These rates are much lower than the average annual application of total N over the 7 years of this study of from 740 to 808 kg N ha^{-1} for MN and CN, respectively (Ferguson and Nienaber, 2000). The field was disked on JD

Table 1
Treatment types, dry matter application rates, and total and available N and P levels applied to irrigated cornfield in 1999

Treatment		Dry matter				
		Applied[a] ($mg\,ha^{-1}$)	Total N[b] ($kg\,ha^{-1}$)	Available N[c] ($kg\,ha^{-1}$)	Total C[b] ($kg\,ha^{-1}$)	Total P[b] ($kg\,ha^{-1}$)
Manure at N rate (MN)	+CC[d]	30.0	273	95.6	2490	57.6
	−CC	24.9	224	78.4	2070	47.8
	Average	27.5[e]	249	87.0	2280	52.7
Compost at N rate (CN)	+CC	39.3	200	50.0	1850	127
	−CC	47.9	244	61.0	2250	155
	Average	43.6	222	55.5	2050	141
Manure at P rate (MP)		0	168	168	0	0
Compost at P rate (CP)		0	168	168	0	0
Fertilizer N (NCK)		0	168	168	0	0

[a] The percent solids of manure and compost were 53.3 and 74.8%, respectively.
[b] N content of manure = 0.91% and compost = 0.51%; C content of manure = 8.3% and compost = 4.7%; P content of manure = 0.192% and compost = 0.323%.
[c] Total N mineralized the first year assumed to be 35% for manure and 25% for compost; P mineralized the first year assumed to be 22% for manure or compost.
[d] +CC: cover crop; −CC: no cover crop.
[e] Average for with and without rye cover crop.

121, worked with a spring-tooth harrow on JD 133, and planted to corn on JD 134 (14 May). A commercial check (NCK) treatment received a side-dressed application of NH_3 at $84\,kg\,N\,ha^{-1}$ ($75\,lb\,acre^{-1}$) on JD 164. On JD 201 urea–ammonium N solution was applied with a high clearance applicator to MP, CP and NCK at a rate of $84\,kg\,N\,ha^{-1}$ ($75\,lb\,acre^{-1}$) of available N on JD 201. The corn was chopped as silage on JD 251 (8 September). The new cover crop of wheat was drilled on JD 263.

2.3. Equipment

A commercial magnetic dipole soil conductivity meter[1] (EM-38, manufactured by Geonics Ltd., 1992)[1] was used in this study. This instrument was operated horizontally and had a response that varies with depth in the soil, yielding a profile weighted electrical conductivity, hereafter designated EC_a, that was centered at a depth of about 0.75 m. Generally, at a transport speed of $6\,m\,s^{-1}$, about 40 samples across the length of each plot were collected with the EM-38 for each pass. The 6.1 m width (eight corn rows) of each plot was about the soil width surveyed by the EM-38.

[1] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

The EM-38 was transported through the field either mounted on a trailer that was pulled behind an all terrain vehicle (ATV) or pulled on a plastic sled by hand when the corn became too tall for the ATV. All reported EC_a measures in this paper have been corrected to the ground surface based measures (Eigenberg et al., 2000). Testing results of the reliability, repeatability, and sensitivity of the EM-38 in discerning field-generated measurements versus artifacts of instrument configuration are given by Eigenberg et al. (2000).

A Trimble PRO-XL GPS[1] (global positioning system) unit was used to obtain positional data. The EM-38 was connected to the GPS unit through a small dedicated battery powered microcomputer (Onset Computer, Model IVa). The GPS unit collects and stores positional data and field EC_a values.

2.4. Soil sampling

Two soil cores (1.91 cm diameter) were taken throughout the growing season with a hand probe from depths of 0–23 cm and 23–46 cm at randomly selected sites within each treatment and cover crop combination. The cores were taken within one day of the EC_a surveys and were analyzed to determine total N, KCl extractable NH_4 and NO_3, and soil moisture content by a local commercial soil testing laboratory.

More extensive soil analyses for soil moisture; total and organic N; KCl extractable NO_3, NH_4, and NO_2; soil pH and electrical conductivity on 1:1 soil to water extracts; and Bray1-P, Ca–P sulfate, and $CaNO_3$ chloride were run on two sample sets, one before (16 March, JD 75) and one after (13 September, JD 252) the corn-growing season. Soil water-filled pore space (WFPS), which is synonymous with soil relative saturation, was calculated from soil gravimetric water content using the following relationship:

$$\mathrm{WFPS} = \frac{\text{volumetric water content } (\mathrm{cm^3\,cm^{-3}})}{\text{total soil porosity } (\mathrm{cm^3} \text{ pore space } \mathrm{cm^{-3}} \text{ soil})}$$

where volumetric water content = gravimetric water content ($\mathrm{g\,H_2O\,g^{-1}}$ soil) × soil bulk density ($\mathrm{g\,cm^{-3}}$ or $\mathrm{mg\,m^{-3}}$), assuming $1\,\mathrm{g\,H_2O} = 1\,\mathrm{cm^3}$ and soil porosity = [1 − (soil bulk density/2.65 (soil particle density)].

Collaborating researchers also sampled soil to a depth of 1.5 m to determine if N or P had leached below the root zone (Ferguson and Nienaber, 2000).

2.5. *Data handling and processing*

Map data were transferred to a PC after each survey, with the stored files converted to ASCII format suitable for input into a contouring and 3-D mapping Surfer® program (Golden Software Inc., 809 14th Street, Golden, CO, 80401-1866). Maps were generated using an inverse distance interpolator.

The scanned points of each treatment strip were formatted (Eigenberg et al., 2000) to be compatible with statistical software (SAS, 1985). The effects of treatment, cover crop and treatment × cover were analyzed using Proc GLM (SAS, 1985). Additionally, correlations of EC_a with NO_3, soil $EC_{1:1}$, and soil water content were computed using Proc Corr (SAS, 1985).

3. Results and discussion

3.1. *EC_a maps*

Presented in Fig. 1 is an EC_a image of the cornfield that was produced at the midpoint (June 14, JD 165) of

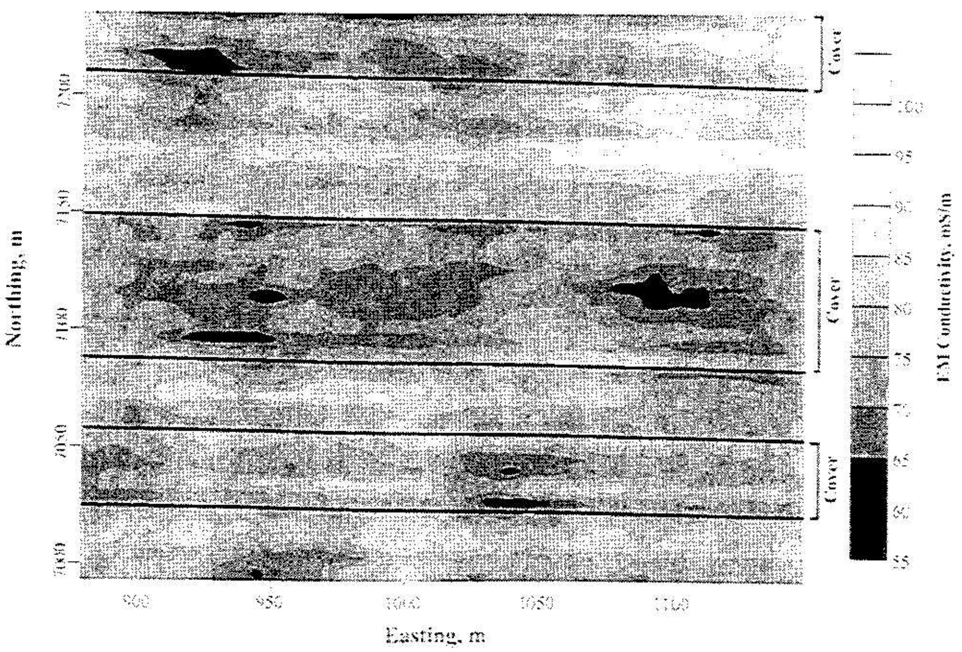
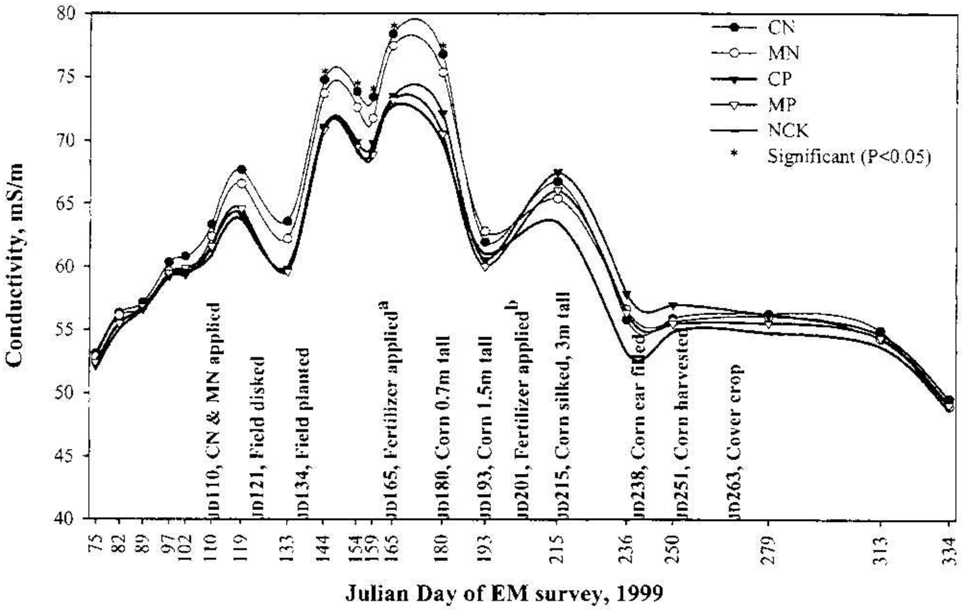


Fig. 1. A representative image of the EC_a map of the cornfield made in the middle of the corn-growing season (JD 165). The cover crop areas are shown and some treatment strips are apparent in the image indicating conductivity differences for the treatments.



[a] Fertilizer applied to NCK plots only

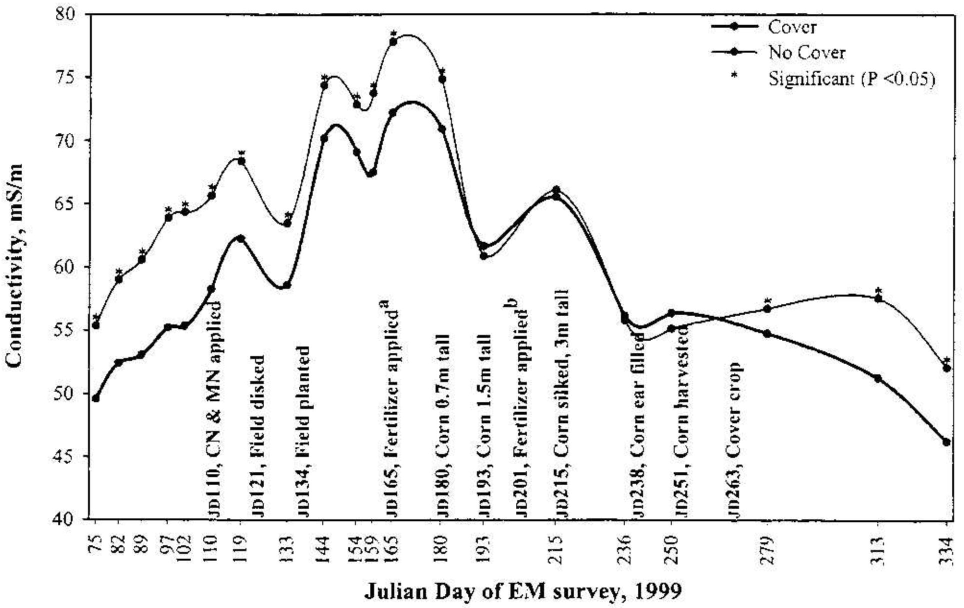
[b] Fertilizer applied to NCK, CP and MP plots

Fig. 2. Seasonal changes in EM38 measured soil profile EC_a as affected by manure (MN, MP), compost (CN, CP), and fertilizer N (NCK) treatments for silage corn at MARC in 1999. Conductivity values plotted represent the average of with and without a rye winter cover crop. Also shown are relevant management and corn growth events during the crop-growing season. Significant differences ($P < 0.05$) between compost and manure treatments and the fertilizer N treatment for each date are indicated by an asterisks (∗) above the plot lines. (a) JD 165, fertilizer applied to NCK plots only; (b) JD 201, fertilizer applied to NCK, MP, and CP plots.

the corn-growing season. When viewed in sequence, the series of maps illustrates the field dynamics with overall EC_a values rising uniformly with time (images not shown). The application of manure and compost produces clearly visible changes in map appearances. Subsequent darkening occurs (lower EC values) in the later maps (JD 180 and beyond) as crop uptake and nutrient transport dominate the image. What is suggested in the images is more evident in the mean values extracted from the image data and illustrated in Fig. 2, that represents average values for each treatment (40 or more readings) averaged across four replicates and the two cover crop treatments. The asterisks in Fig. 2 indicate significant differences ($P < 0.05$) in treatments as compared to the commercial fertilizer check treatment (NCK). The EC_a of MN and CN treatments trended higher than other treatments for a 2-month period (JD 119–180) after application of manure and compost on JD 110 (20 April), and were significantly greater for more than one month (JD 144–180). This likely resulted from mineralization of residual and freshly applied N from manure and compost and the addition of salts and available N as NH_4 and NO_3. Treatment effects were similar between cover crop treatments except, as discussed by Eigenberg et al. (2000), EC_a mean values for the portion of the field receiving the CN treatment without cover were significantly different from the NCK from the beginning of the season (JD 75) through crop harvest on JD 236 (data not shown).

3.2. Soil electrical conductivity as an indicator of biophysical changes in plant available N

Seasonal changes in soil electrical conductivity for silage corn with and without a rye cover crop for 1999 are shown in Fig. 3. In general, EC_a for all treatments increased from mid-March (JD 75) through mid-June



[a] Fertilizer applied to NCK plots only

[b] Fertilizer applied to NCK, CP and MP plots

Fig. 3. Comparison of EM-38 measured soil electrical conductivities with and without a rye winter cover crop. The presence of a rye cover crop resulted in significantly lower soil electrical conductivity levels through periods of the year when the cover crop was growing and corn was not in the active growth phase. Significant differences ($P < 0.05$) between the rye cover crop and no cover crop for each date are indicated by an asterisks (*) above the plot lines. Also, shown are relevant management and corn growth events during the crop-growing season at MARC in 1999. (a) JD 165, fertilizer applied to NCK plots only; (b) JD 201, fertilizer applied to NCK, MP, and CP plots.

(JD 165) when ammonium fertilizer N was applied to the N check plot when corn was almost 30 cm tall (four to six leaf stage). Conductivity declined thereafter throughout the growing season, reaching values at or below the initial early spring values about three months after corn silage harvest.

The trends observed for EC_a during the growing season generally paralleled changes in soil temperature throughout the year, particularly for the 5 cm soil depth (Fig. 4). Soil microbial activity doubles with each 10°C increase in temperature between 10 and 35°C (Parkin et al., 1996). Thus, the increases in EC_a with increasing temperature apparently followed a trend similar to that for microbial activity. The peaks in soil temperature throughout the year, however, were out of phase with those for conductivity, with the conductivity peaks lagging the soil temperature peaks by 5–7 days. If conductivity is a good indicator of the dynamics of soil available NO_3 levels, as suggested by Smith and Doran (1996), this may have resulted from the two-step process of organic N mineralization. The formation of the first product (NH_4) is brought about by many different microorganisms over a wide range of soil conditions. The second step, the oxidation of NH_4 to NO_3, is brought about by a select group of aerobic bacteria that are more sensitive to soil temperature, soil water content, and oxygen availability. Another explanation for the out of phase nature of temperature and EC_a is the fact that sudden declines in soil temperature are associated with rainfall events, especially during the early growing season. The delayed declines in EC_a observed may be associated with the loss of NO_3 from soil due to leaching or denitrification that occur under wet soil conditions after rainfall (Fig. 4).

The declines in EC_a (Fig. 3) that were observed between JD 121 and 134 and between JD 145 and 159 were apparently related to soil conditions which

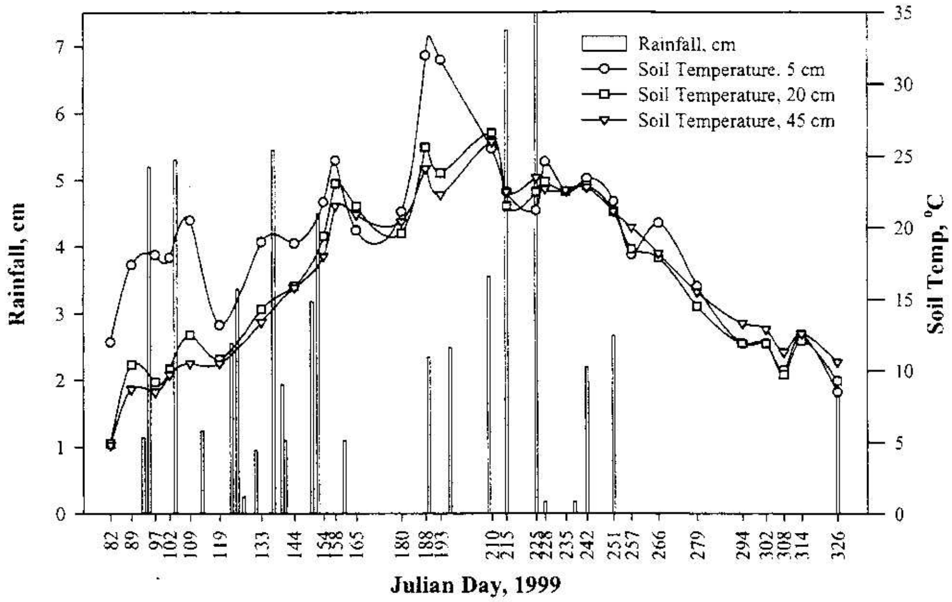


Fig. 4. Soil temperatures and precipitation events (rainfall and center-pivot irrigation) for the manure management plots at MARC, Clay Center, NE for 1999.

approached saturation during these periods (Eigenberg et al., 2000). Although fluctuations in soil water content were partially associated with oscillations in EC_a, it is obvious that water and nutrient uptake characteristics of growing corn were the major factors controlling soil electrical conductivity later in the growing season. This period in the growing season occurred between JD 165, when commercial fertilizer was applied to the N check when corn was about 30 cm tall, and on JD 251 when corn silage was harvested (Fig. 3). It is interesting to note that the downward trend in soil EC_a was reversed between JD 193 and 215 at which time the corn was 2–3 m tall and in the silking stage. Also, as mentioned earlier, 84 kg N ha^{-1} urea–ammonium N solution was applied on JD 201 to MP, CP and NCK treatments. Researchers have noted that during silking of corn there is very little uptake of N, regardless of soil moisture condition and plant stress (James Schepers, personal communication, November 1999 (Schepers, 1999)).

The soil EC_a values observed in this study, 52–78 mS m^{-1} (0.52–0.78 dS m^{-1}), were generally below the threshold of 0.8–1.0 dS m^{-1} (soil:water, 1:1), above which the growth and activity of plants and microorganisms can be significantly altered (Smith and Doran, 1996). However, the results of this study suggest that soil electrical conductivity may serve as a useful indicator of available N in soil as suggested by Gajda et al. (2000) and Patriquin et al. (1993). Throughout the year, when corn was not in an active growth phase, the presence of rye as a growing cover crop resulted in significantly lower levels of EC_a (Fig. 3). In general, the lower soil EC_a values with the growing cover crop were also associated with lower levels of NO_3 in the soil (Eigenberg et al., 2000). However, after disking and incorporation of the cover crop on (JD 121), soil NO_3 levels increased intermittently until JD 180 in cover crop plots, especially those receiving manure and compost (MN and CN). During this period two declines in conductivity after JD 119 and 144 were associated with brief rainfall periods which resulted in the soil approaching or exceeding saturation. Under these conditions, soluble NO_3–N would be expected to be lost due to leaching or denitrification. Parkin et al. (1996) demonstrated that considerable N can be lost from soil by denitrification when soil water content exceeds 80% water-filled pore space (80% relative saturation).

It appears from this study that the mineralization and loss of available N from soil can be reasonably estimated from soil electrical conductivity values. The average change in soil EC_a between JD 110, when compost and manure were added to soil, and JD 165, before corn started removing appreciable available N, with and without a winter cover crop averaged 0.14 and 0.12 dS m^{-1} (14 and 12 mS m^{-1}). This equates to 19.6 and 16.8 ppm available mineral N, respectively (Smith and Doran, 1996; EC (dS m^{-1}) $\times$ 140 ppm N (dS $m^{-1})^{-1}$ = microgram of available N g^{-1} soil). Assuming an average soil bulk density of 1.35 g cm^{-3} and a soil depth of 60 cm, 159 and 136 kg N ha^{-1} of gross N was mineralized over 55 days for the cover and no cover treatments, respectively. Declines in EC_a occurred between JD 119 and 133, and between JD 144 and 159 were 0.063 and 0.055 dS m^{-1}, respectively. These losses, apparently associated with N losses due to leaching and or denitrification, represented NO_3–N losses of 71 and 62 kg N ha^{-1} for cover crop and no cover, respectively. Subtraction of EC_a estimated N losses from the EC_a estimated gross N mineralized during this 55 day period results in an estimated net N available to corn plants of 88 and 74 kg N ha^{-1} on cover and no cover plots, respectively, equivalent to a plant available N net formation rate of 1.6–1.3 kg N ha^{-1} per day. This is similar to the range of 0.8–1.1 kg N ha^{-1} per day for soil from the same treatments that were incubated in the laboratory under ideal conditions of moisture and temperature (data not shown). Based on laboratory analyses for soil NO_3–N concentrations in the top 0–46 cm of soil between JD 110 and 165, the average N mineralized from all treatments of the cover and no cover plots were 83 and 56 kg N ha^{-1}, respectively. This equates to an average mineralization rate of 1.5 and 1.0 kg N ha^{-1} per day. From this, EC_a appeared to be a reliable indicator of soluble N gains and losses in soil, and should serve as a reliable indicator of sufficiency of available N for corn early in the growing season and as an indicator of N surplus after harvest.

3.3. Soil electrical conductivity ($EC_{1:1}$) as influenced by available N and soil water content

At the beginning of the growing season (JD 75), the levels of NH_4 and NO_3 in the 0 to 46 cm soil layer ranged from 19 to 39, and from 3 to 17 kg N ha^{-1}, respectively (Table 2). The NO_3 levels in the cover crop soils were significantly lower than those without a cover crop, indicating that the cover crop had utilized N remaining in the soil after harvest of the previous corn crop. Also, the proportion of the total soil electrical conductivity that was due to NO_3–N was higher without (8–20%) than with a cover crop (3–13%). The proportion of the total conductivity due to total available N (NH_4 and NO_3) was higher and ranged from 34–58% across cover treatments as compared to no winter cover. For soil samples taken on 13 September (JD 252), at the end of the growing season, NH_4 levels were similar between all treatments but NO_3 levels tended to be slightly higher where there was no cover crop (Table 3). Also, the proportion of conductivity that was due to NO_3–N and (NH_4–N + NO_3–N) tended to be higher where there was no cover crop and ranged from 9 to 31%, and from 14 to 40%, respectively.

Table 2
Soil NH_4–N and NO_3–N levels, electrical conductivity (soil:water, 1:1), and the proportion of conductivity from NO_3 and NH_4 in samples from 0 to 46 cm layer sampled on 16 March 1999 (JD 75) with (+CC) and without (−CC) a rye winter cover crop on the manure management plots at MARC

Treatment	NH_4–N ($\mu g\,g^{-1}$)		NO_3–N ($\mu g\,g^{-1}$)		1:1 Electrical conductivity (dS m^{-1})		% of $EC_{1:1}$[a] NO_3		% of $EC_{1:1}$[a] NH_4 + NO_3	
	+CC	−CC	+CC	−CC	+CC	−CC	+CC	−CC	+CC	−CC
Manure @ N rate (MN)	27.2	28.5	3.0	15.6	0.64	0.61	3.1	18.4	33.6	51.6
Compost @ N rate (CN)	23.9	29.0	1.8	16.8	0.53	0.62	2.5	19.5	34.7	53.2
Manure @ P rate (MP)	38.8	29.6	2.0	12.3	0.50	0.52	3.0	16.9	58.4	57.7
Compost @ P rate (CP)	19.7	30.8	9.8	13.8	0.53	0.59	13.2	16.6	39.8	54.1
Fertilizer N (NCK)	19.2	25.3	1.5	5.4	0.45	0.47	2.5	8.3	37.0	55.9

[a] The 1:1 electrical conductivity attributable to NO_3 or NO_3 + NH_4 is calculated by dividing the total amount ($\mu g\,g^{-1}$) of each species by 140 $\mu g\,g^{-1}$ per dS m^{-1} conductivity.

Table 3
Soil NH_4–N and NO_3–N levels, electrical conductivity (1:1, soil:water), and the proportion of conductivity from NO_3 and NH_4 in samples from the 0 to 46 cm layer sampled on 13 September 1999 (JD 252) with (+CC) and without (−CC) a rye winter cover crop on the manure management plots at MARC

Treatment	NH_4–N ($\mu g\,g^{-1}$)		NO_3–N ($\mu g\,g^{-1}$)		1:1 Electrical conductivity ($dS\,m^{-1}$)		% of $EC_{1:1}$[a] NO_3		% of $EC_{1:1}$[a] $NH_4 + NO_3$	
	+CC	−CC	+CC	−CC	+CC	−CC	+CC	−CC	+CC	−CC
Manure @ N rate (MN)	4.4	3.9	4.8	6.3	0.55	0.52	6.2	8.6	11.9	14.0
Compost @ N rate (CN)	4.2	3.9	16.4	10.3	0.54	0.51	22.0	14.5	27.5	19.9
Manure @ P rate (MP)	4.7	5.0	6.2	13.4	0.34	0.36	12.8	26.7	22.6	36.6
Compost @ P rate (CP)	4.0	5.1	2.8	4.8	0.36	0.40	5.6	8.8	13.5	17.8
Fertilizer N (NCK)	5.4	5.2	2.3	17.4	0.36	0.40	4.6	31.0	15.7	40.0

[a] The 1:1 electrical conductivity attributable to NO_3 or $NO_3 + NH_4$ is calculated by dividing the total amount ($\mu g\,g^{-1}$) of each species by $140\,\mu g\,g^{-1}$ per $dS\,m^{-1}$ conductivity; proportion of $EC_{1:1}$ is then calculated by ($EC_{1:1}$ of ion(s)/$EC_{1:1c}$ soil) × 100.

It was interesting to note that the 'background' total soil electrical conductivity ($EC_{1:1}$) tended to decline from the beginning (Table 2) to the end (Table 3) of the growing season, and more so in treatments that did not receive recent organic amendments. The $EC_{1:1}$ of MN and CN treatments had declined slightly from an average of $0.60\,dS\,m^{-1}$ in mid-March to a value of $0.53\,dS\,m^{-1}$ in mid-September. However, the $EC_{1:1}$ of treatments not receiving recent organic amendments (MP, CP, and NCK) decreased from 0.51 to $0.37\,dS\,m^{-1}$ over the same period. Under field conditions, decreases in 'background' conductivity are due in part to reductions in soil water content and available soil organic levels as the season progresses.

In this research study, profile weighted soil electrical conductivity values (EC_a to about 75 cm) using the EM_{38} were highly correlated with soil NO_3–N in the surface 0–23 and 23–46 cm soil layers throughout the growing season (Table 4). Correlations in surface soil (0–23 cm) were absent or less pronounced for treatments not receiving recent additions of manure or compost but did exist at the second depth (23–46 cm). Significant correlations were also found between EM_{38} soil electrical conductivity measurements and soil water content as measured by water-filled pore space at both soil depths. These correlations, however, were not as high as those for NO_3–N.

Table 4
Pearson's correlation coefficients of surface soil electromagnetic conductivity measured with the EM38 and soil NO_3–N and H_2O (relative saturation) contents for soil depths of 0–23 and 23–46 cm with (+CC) and without (−CC) a rye winter cover crop at 18 times during the growing season on the MARC manure management plots in 1999

Treatment	Cover crop	0 to 23 cm NO_3–N ($\mu g\,g^{-1}$)	Soil depth soil H_2O WFPS[a]	23 to 46 cm NO_3–N ($\mu g\,g^{-1}$)	Soil depth soil H_2O WFPS[a]
Manure @ N rate (MN)	+CC	0.79***	0.49*	0.81***	0.50*
	−CC	0.48*	0.58*	0.79***	0.50*
Compost @ N rate (CN)	+CC	0.71***	0.59**	0.49*	0.59**
	−CC	0.48*	0.50*	0.86***	0.44
Manure @ P rate (MP)	+CC	0.52*	0.64**	0.47*	0.72***
	−CC	0.16	0.48*	0.68***	0.50*
Compost @ P rate (CP)	+CC	0.34	0.31	−0.25	0.35
	−CC	−0.11	0.54*	0.55*	0.55*
Fertilizer N (NCK)	+CC	0.08	0.58*	0.60**	0.10
	−CC	−0.23	0.58*	0.16	0.37

[a] Soil WFPS is synonymous with relative saturation.
*** Indicate significant correlations at $P < 0.001$, respectively.
** Indicate significant correlations at $P < 0.01$, respectively.
* Indicate significant correlations at $P < 0.05$, respectively.

The utility of soil electrical conductivity as a measure of the mineralization and release of soil available N depends on several factors, including seasonal changes in soil water content and the relative proportion of the 'background' conductivity signal, which is attributable to mineralized available N (De Neve et al., 2000). Our analyses for 1999 did not permit a complete evaluation of the proportion of the soil electrical conductivity signal resulting from NO_3 and ($NO_3 + NH_4$) throughout the entire growing season. However, preliminary results from the year 2000 indicated that, among soil anions, NO_3 accounts for 25–35% of the soil conductivity signal ($EC_{1:1}$) followed in order of predominance by HCO_3 (25–30%), SO_4 (10–25%), Cl (10–15%), and PO_4 (2–5%).

4. Conclusions

Field measurement of soil electrical conductivity (EC_a) identified the effects of manure, compost, fertilizer N, and cover crop treatments on changes in available N levels before, during, and after the corn-growing season (Figs. 2 and 3). Recently applied compost and manure at the N rate resulted in consistently higher conductivity and levels of available N followed by compost and manure at the P rate, which hadn't been applied since 1997. The N fertilizer treatment (NCK), unlike manure and compost treatments, tended to have the lowest soil conductivity and least residual effect after application. Ferguson and Nienaber (2000) reported that average corn silage yield over 7 years, with application of organic residues, was equal to or greater than that from inorganic N fertilizer. With the 1999 crop continuing the same trend, the 1999 yields for the MN and CN treatments were observably higher than MP and CP, and NCK resulted in the lowest yield. Sequential measurement of profile weighted soil electrical conductivity (EC_a) was effective in identifying the dynamic changes in available soil N, as affected by animal manure and N fertilizer treatments, during the corn-growing season. This method also clearly identified the effectiveness of cover crops in minimizing levels of available soil N before and after the corn-growing season, when soluble N is most subject to loss. Ferguson and Nienaber (2000) reported that use of a winter cover crop was effective in reducing NO_3 accumulation and leaching from high rates of organic applications (MN and CN) on this experimental field. In 1999, the winter cover crop significantly reduced residual NO_3–N at all depths below 0.15 m to a depth of 1.5 m; from 76 kg N ha^{-1} with no cover crop to 34 kg N ha^{-1} where a rye winter cover crop was planted. Time sequence EC_a maps provided insights into temporal soil dynamics revealing identifiable differences in rates of change of soil conductivity, and apparently available N, among treatments. Soil conductivity appeared to be a reliable indicator of soluble N gains and losses in soil and may serve as a measure of N sufficiency for corn early in the growing season. Soil conductivity may also be used as an indicator of N surplus after harvest when N is prone to loss from leaching and/or denitrification.

References

Brune, D.E., Doolittle, J., 1990. Locating lagoon seepage with radar and electromagnetic survey. Environ. Geol. Water Sci. 16, 195–207.

Corwin, D.L., Rhoades, J.D., 1982. An improved technique for determining soil electrical conductivity — depth relations form above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46, 517–520.

De Neve, S., Van De Steene, J., Hartman, R., Hofman, G., 2000. Using time domain reflectometry for monitoring mineralization of nitrogen from soil organic matter. Eu. J. Soil Sci. 51, 295–304.

Doran, J.W., Kessavalou, A., Hutchinson, G.L., Vigil, M.F., Halvorson, A.D., 1996. Influence of cropping/tillage management on soil fertility and quality of former CRP land in the central high plains. In: Proceeding of the Great Plains Soil Fertility Conference, Denver, CO, March 1996.

Eigenberg, R.A., Korthals, R.L., Nienaber, J.A., 1996. Electromagnetic survey methods applied to agricultural waste sites. Amer. Soc. Agricul. Engr. Paper No. 963014, ASAE, St. Joseph, MI 49085.

Eigenberg, R.A., Doran, J.W., Nienaber, J.A., Woodbury, B.L., 2000. Soil conductivity maps for monitoring temporal changes in an agronomic field. In: Proceedings of the 8th International Symposium on Animal Agriculture and Food Processing Wastes, Des Moines, IA, 9–11 October, 2000, 249–265.

Ferguson, R.B., Nienaber, J.A., 2000. Composted beef feedlot manure application impacts on nitrogen and phosphorus accumulation and movement in soil. In: Proceedings of the 8th International Symposium on Animal, Agricultural and Food Processing Wastes, Des Moines, IA, 9–11 October 2000, 719–727.

Gajda, A.M., Doran, J.W., Wienhold, B.J., Kettler, T.A., Pikul Jr., J.L., Cambardella, C.A., 2000. Soil quality evaluations of alternative and conventional management systems in the Great

Plains. In: Lal, R., Kimble, J.F., Follett, R.F., Stewart, B.A. (Eds.), Methods of Assessment of Soil Carbon. CRC Press, Boca Raton, FL.

Geonics, 1992. EM 38 Operating Manual. Geonics Limited, Mississauga, Ont., Canada.

McNeill, J.D., 1990. Use of electromagnetic methods for groundwater studies. In: Ward, S.H. (Ed.), Investigations in Geophysics No. 5. Geotechnical and Environmental GeophysicsSociety of Exploration Geophysicists, Tulsa, OK.

Parkin, T.B., Doran, J.W., Franco-Vizcaino, E., 1996. Field and laboratory tests of soil respiration. In: Doran, J.W., Jones, A.J. (Eds.), Method for Assessing Soil Quality. Soil Sci. Soc. Am. Special Publication 49, SSSA, Madison, WI.

Patriquin, D.G., Blaikie, H., Patriquin, M.J., Yang, C., 1993. On-farm measurements of pH, electrical conductivity, and nitrate in soil extracts for monitoring coupling and decoupling of nutrient cycles. Biol. Agric. Hort. 9, 231–272.

Ranjan, R.S., Karthigesu, T., Bulley, N.R., 1995. Evaluation of an electromagnetic method for detecting lateral seepage around manure storage lagoons. Am. Soc. Agric. Eng. Paper No. 952440, ASAE, St. Joseph, MI 49085.

SAS, 1985. SAS User's Guide: Statistics. SAS Institute Inc., Cary, NC.

Schepers, J., 1999. Personal communication. Soil and Water Conservation Research Unit, University of Nebraska, Lincoln, Nebraska.

Smith, J.L., Doran, J.W., 1996. Measurement and use of pH and electrical conductivity for soil quality analysis. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Sci. Soc. Am. Special Publication 49. SSSA, Madison, WI.

Sudduth, K.A., Kitchen, N.R., 1993. Electromagnetic induction sensing of claypan depth. Am. Soc. Agric. Eng. Paper No. 931531, ASAE, St. Joseph, MI 49085.

Sudduth, K.A., Drummond, S.T., Kitchen, N.R., 2000. Measuring and interpreting soil electrical conductivity for precision agriculture. Second International Geospatial Information in Agriculture and Forestry Conference, Lake Buena Vista, FL, 10–12 January 2000.

Williams, B.G., Baker, G.C., 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Austr. J. Soil Res. 20, 107–118.